Integration of PV into System Operations

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Project Objectives and Key Questions Addressed

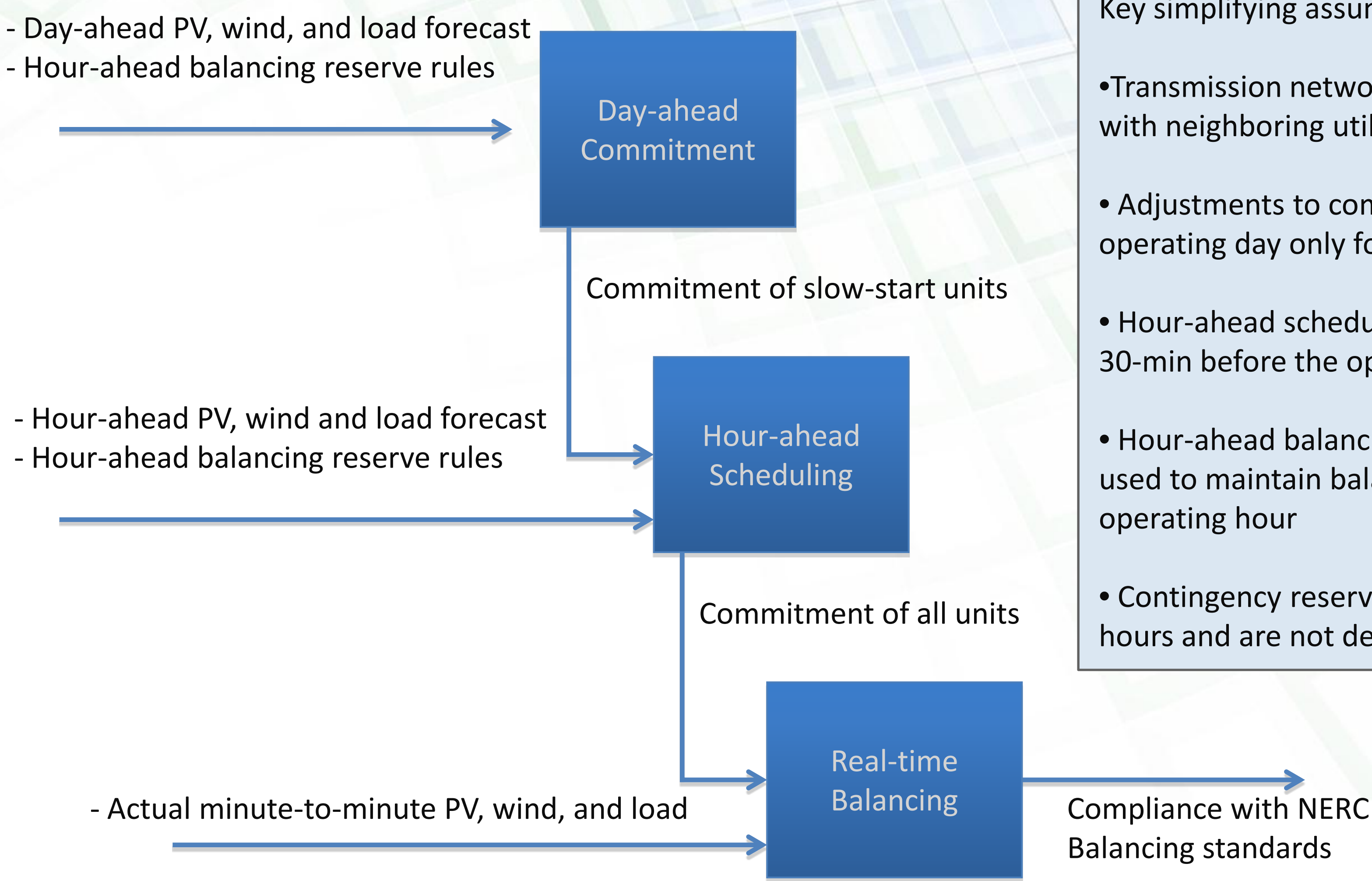
- Project objectives
  - Improve understanding of operational challenges from large-scale expansion of PV with focus on intra-hour variability and operating reserve requirements
  - Improve state-of-the-art tools and methodologies for power system operations with PV
  - Conduct a detailed case study of Arizona Public Service Company (APS)

- Key questions
  - How much additional operating reserves are needed to maintain reliability?
  - How do operations change?
  - What is the additional cost?
  - What are cost effective solutions to address uncertainty and variability in PV?

Approach

- Detailed discussions with APS staff from three functional areas:
  - (1) Resource planning, (2) generation scheduling, (3) transmission system operations
- Developed modeling framework to mimic key parts of decision making process
- Apply that framework to case study of APS with and without PV in future year
- Evaluate performance under different scenarios focusing on three key metrics:
  - Integration costs
  - Reliability (as measured by average CPS 2 score)
  - Renewable curtailment

Simulation Framework for Utility Operations

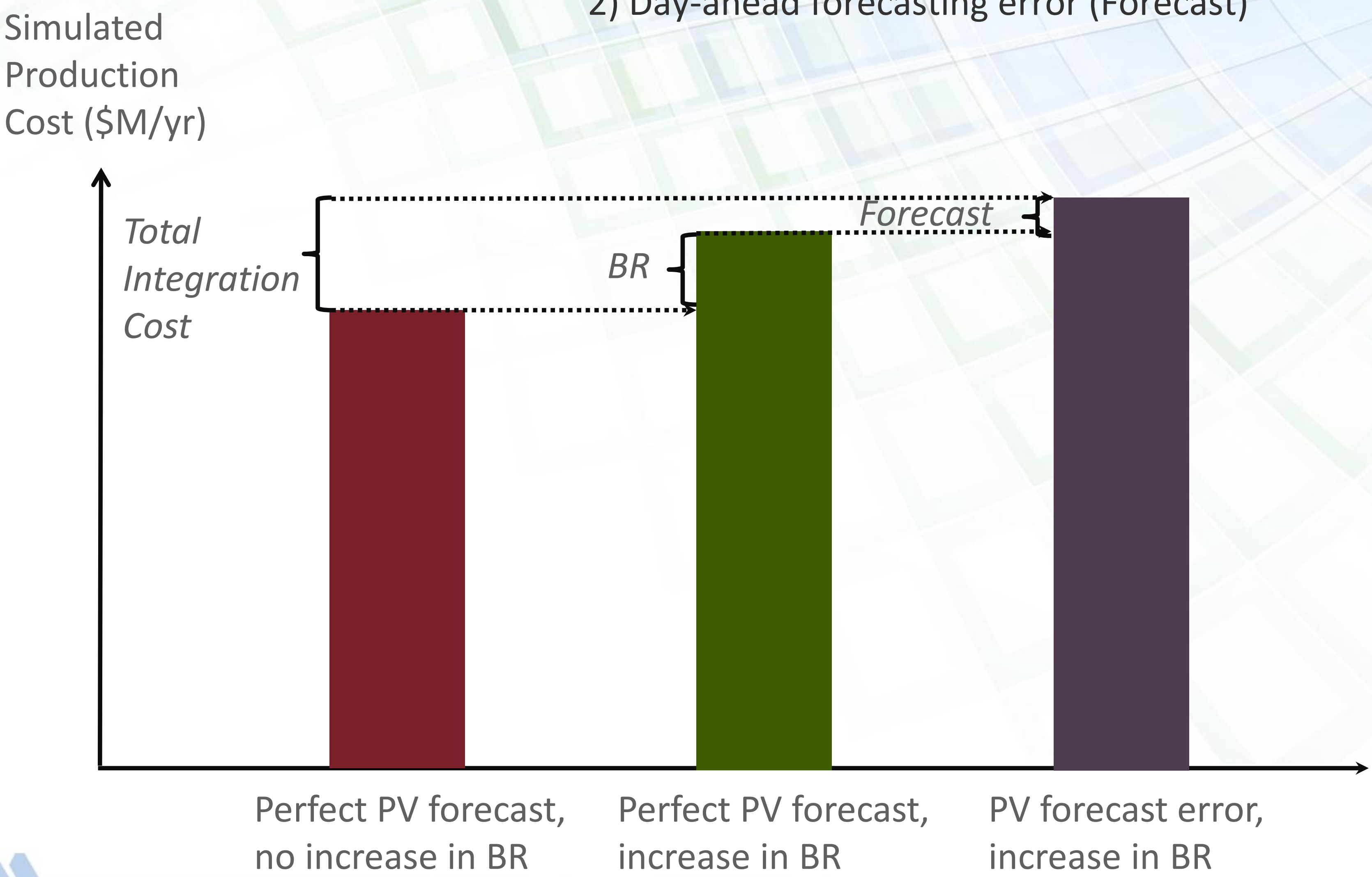


Key simplifying assumptions:

- Transmission network and exchange with neighboring utilities ignored
- Adjustments to commitments within operating day only for fast-start units
- Hour-ahead schedules are finalized 30-min before the operating hour
- Hour-ahead balancing reserves are used to maintain balance within the operating hour
- Contingency reserves are held in all hours and are not deployed

Defining PV Integration Costs

- Integration cost has two components: 1) Increase in hour-ahead balancing reserves (BR)
  2) Day-ahead forecasting error (Forecast)

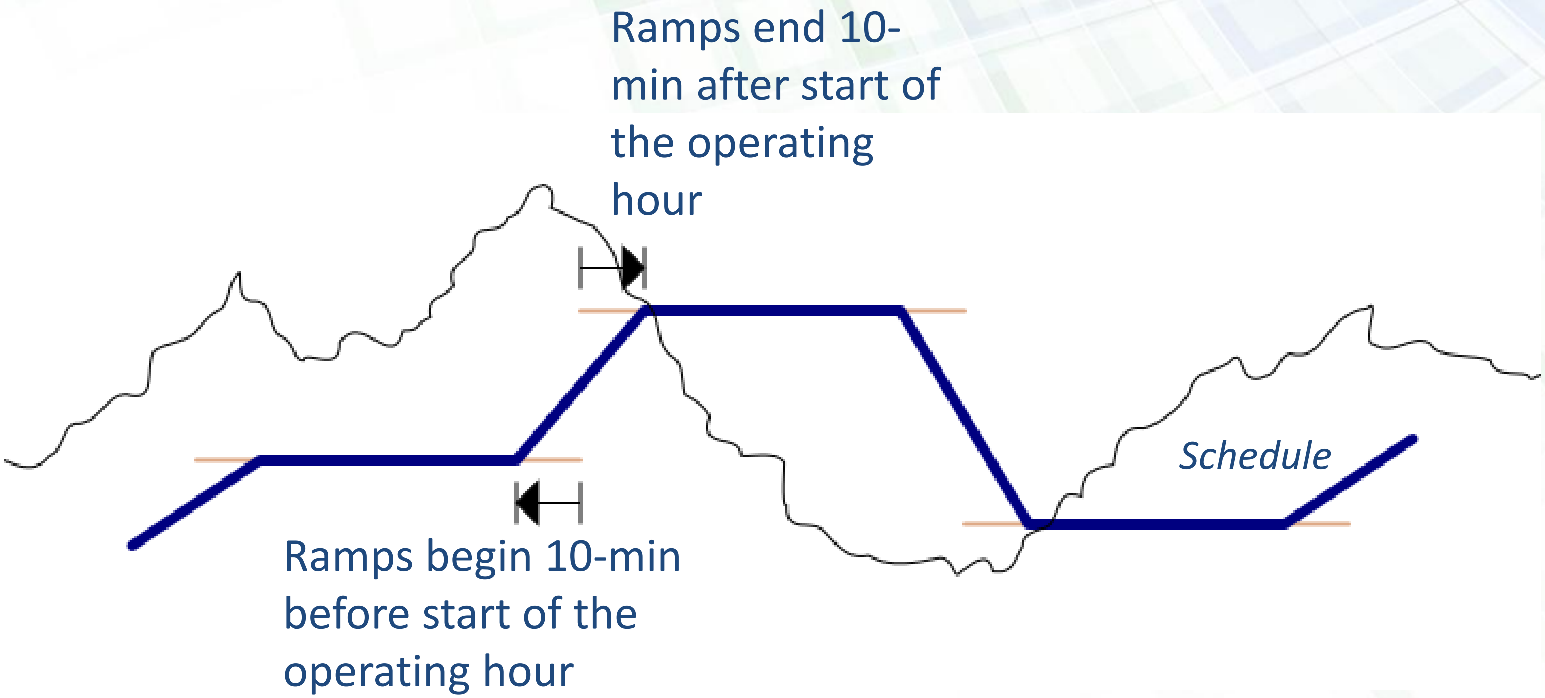


Balancing Reserves are Based on Deviations from Hour-Ahead Schedule

Hour-Ahead schedules are based on forecasts made 30-min prior to the start of the operating hour:

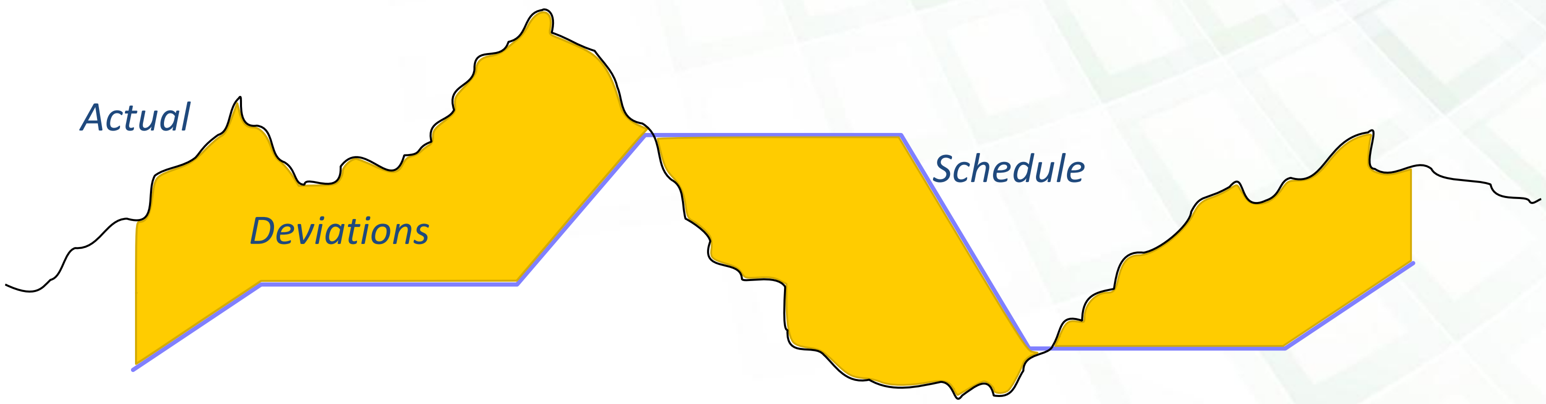
- *PV: 30 min "persistence of cloudiness"*
- *Wind: 30 min persistence*
- *Load: Historical HA forecasts*

Balancing Reserves
are Based on Deviations from Hour-Ahead Schedule



Hour-Ahead schedules include 20-min ramps between hours

Balancing Reserves are Based on Deviations from Hour-Ahead Schedule



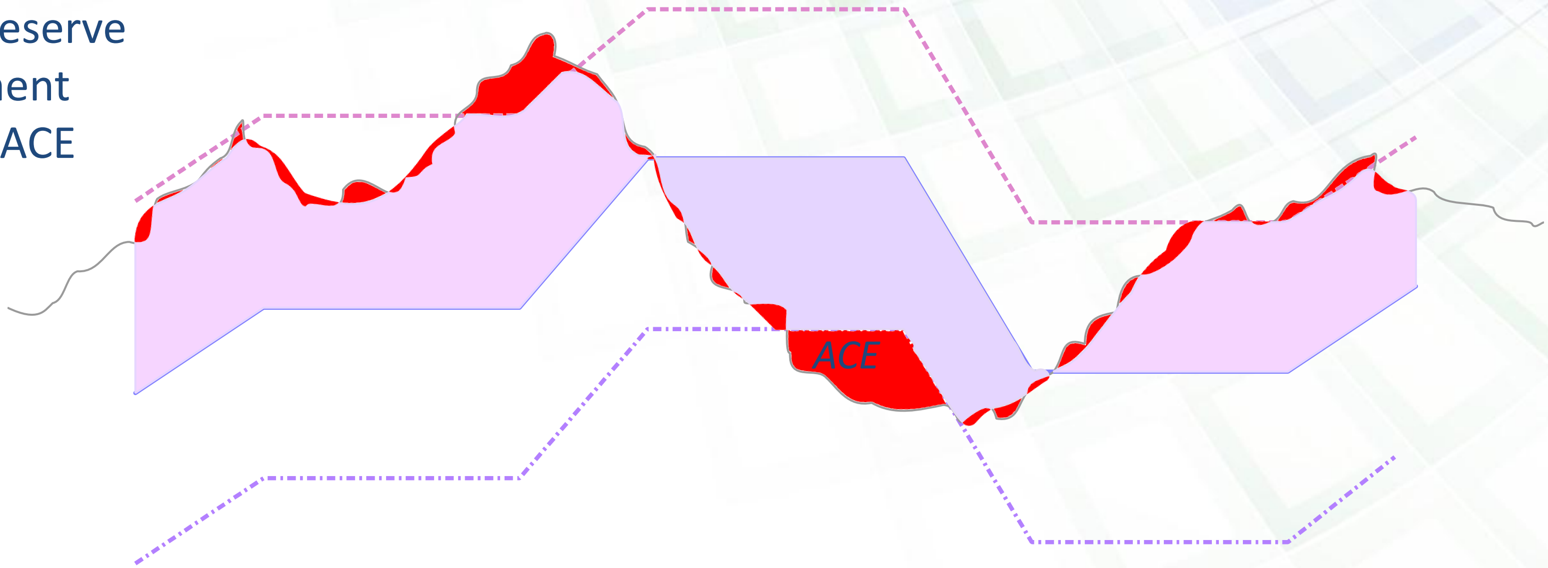
Deviations are based on the difference between the actual 1-min generation and Hour-Ahead schedule

Balancing Reserves are Based on Deviations from Hour-Ahead Schedule

Hour-ahead balancing reserves are set to a level that covers 95% of 1-min deviations

Are Balancing Reserves Sufficient? Check by Calculating the CPS 2 Score for Actual Year

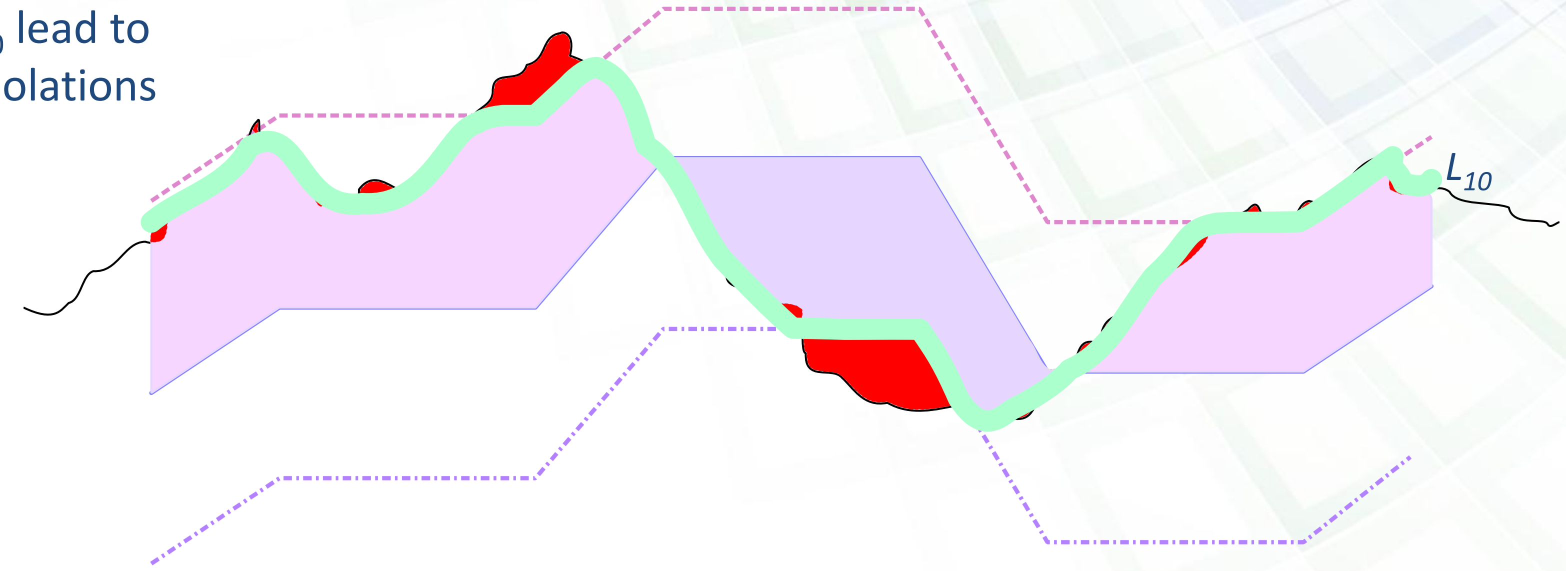
Deviations not met by reserve deployment leads to ACE



Simulate the effectiveness of the balancing reserve rules by deploying the balancing reserves within the operating hour

Are Balancing Reserves Sufficient? Check by Calculating the CPS 2 Score for Actual Year

Only ACE greater than L_{10} lead to CPS 2 violations



CPS 2 score is based on comparison of 10-min average ACE to L_{10}.

Case study: APS in 2027 with Increased Solar PV

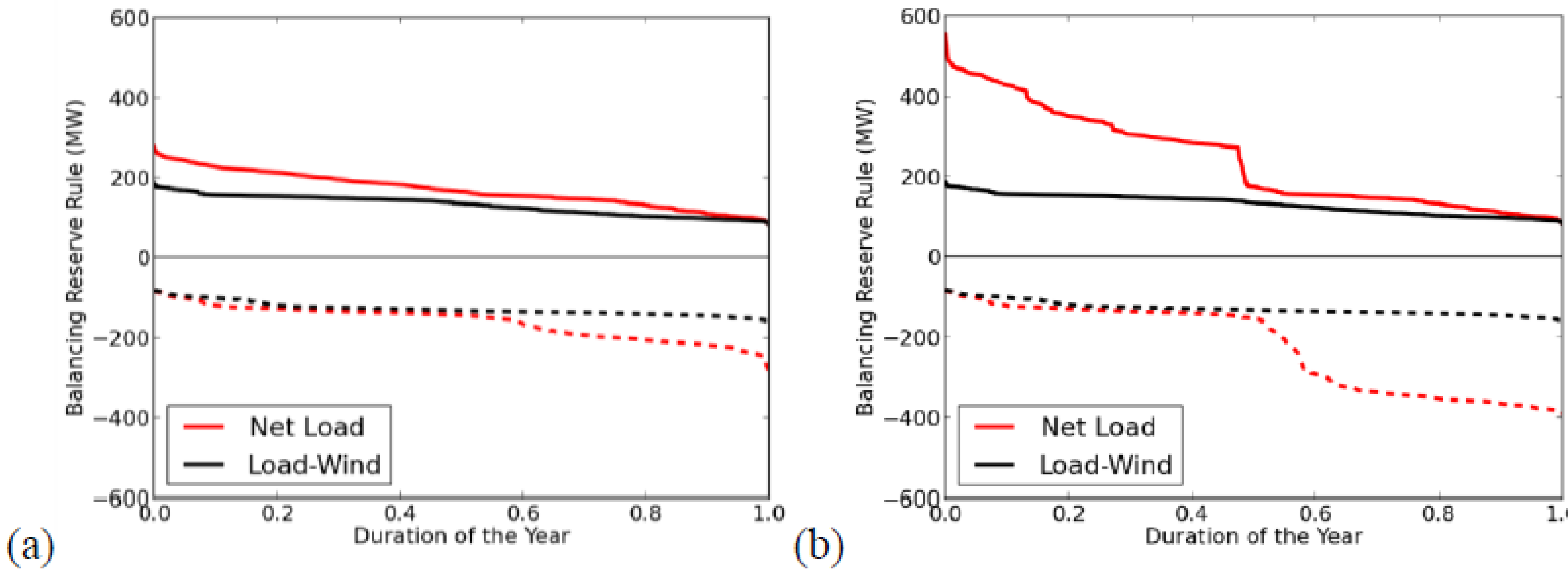
Two main cases:

	Low PV	High PV
PV nameplate capacity	1,674 MW	2,974 MW
PV penetration (% Energy)	9%	17%
Wind penetration (% Energy)	5%	5%

Forecasting errors:

	Normalized Mean Absolute Error (NMAE)				Normalized Mean Square Error (NMSE)			
	Load	Wind	Low PV	High PV	Load	Wind	Low PV	High PV
Day-ahead	1.9%	12.7%	3.2%	3.5%	2.7%	17.2%	7.7%	8.4%
Hour-ahead	0.2%	4.4%	1.3%	1.6%	0.3%	6.4%	2.8%	3.4%

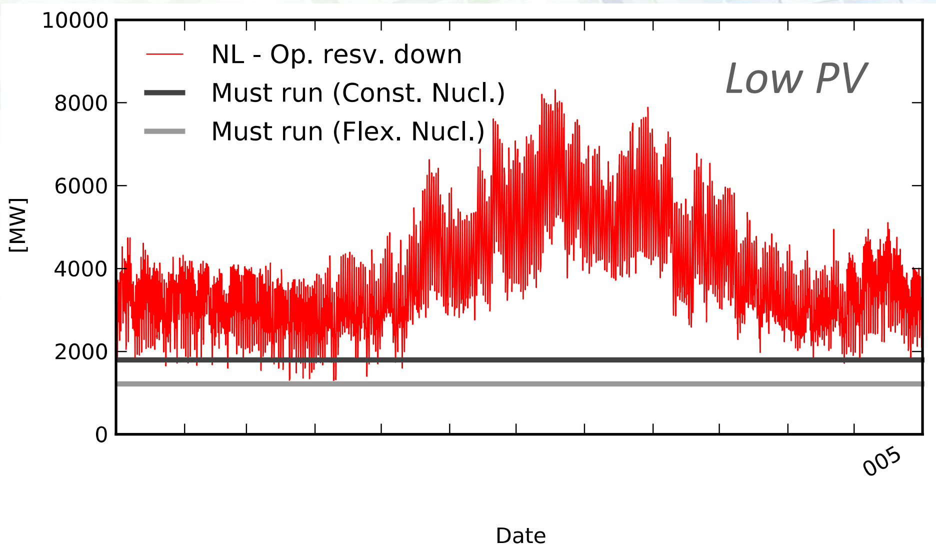
Hour-Ahead Balancing Reserves

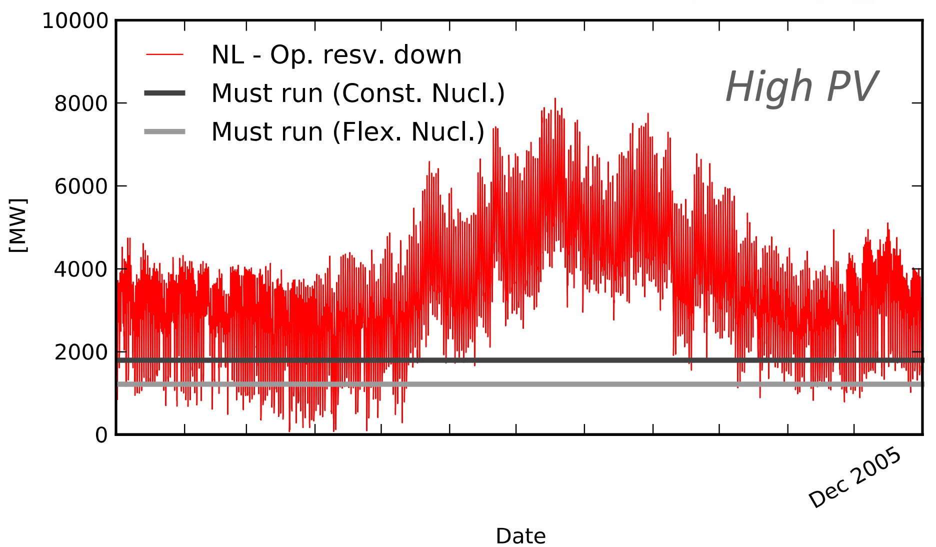


Note: Solid line is the balancing reserve requirement in the up direction; dashed line is the balancing reserve requirement in the down direction. Hourly balancing reserve requirements in each direction are sorted from highest to lowest to create an exceedance curve.

Figure 7. Balancing Reserve Requirements for Load-Wind and for Net Load (load, wind, and PV) over the Year in the Low-PV Scenario (a) and High-PV Scenario (b)

Increased PV Deployment Requires more Flexibility, Particularly during Low Net-load (NL) Periods

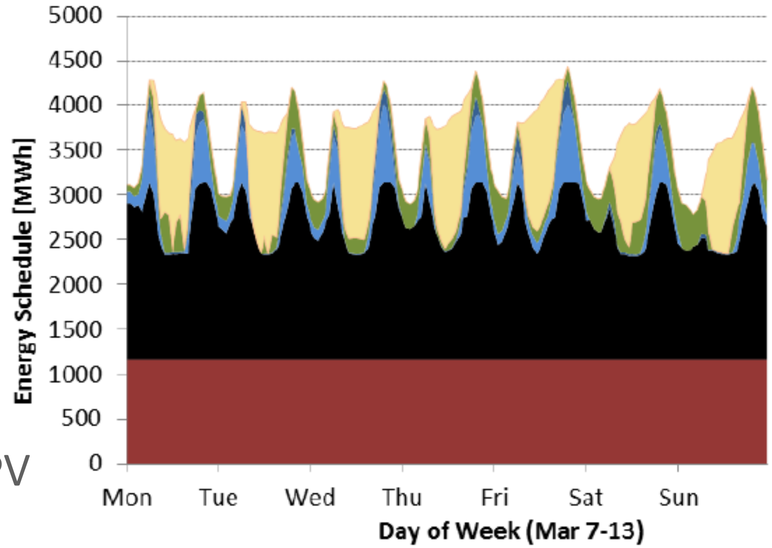


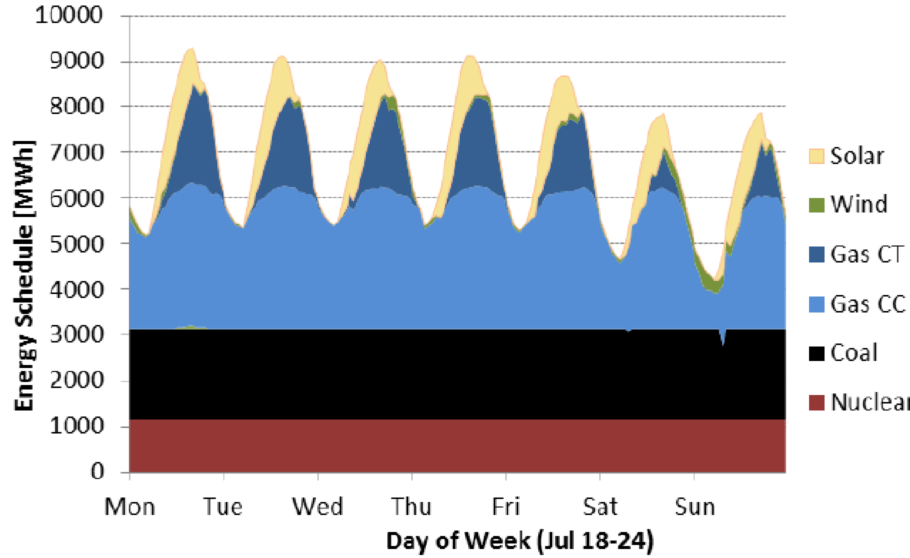


- PV or wind generation lead to decrease in output from APS power plants
- In certain conditions, APS generation is not able to sufficiently reduce output
- Must-run coal and inflexible nuclear drive need to curtail renewable generation
- We chose to model "flexible nuclear" as potential solution
- Other alternatives include allowing must-run coal plants to de-commit and selling excess power, primarily during spring days

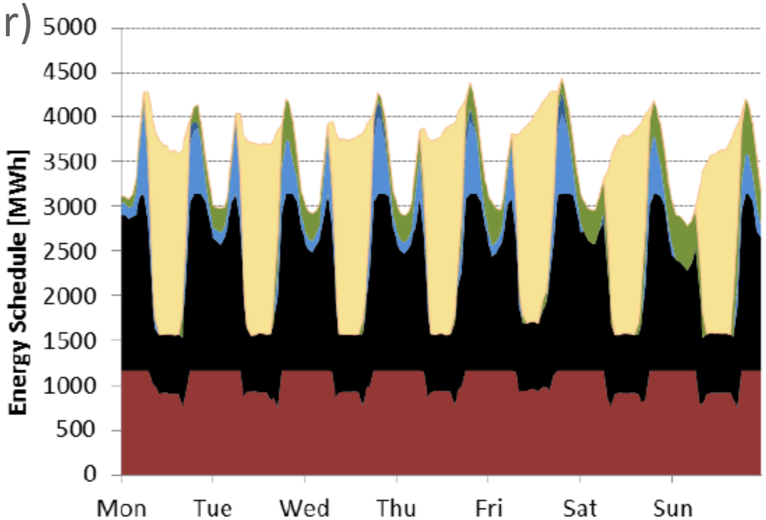
Minimum Net-Load Periods in the Spring Require Large Downward Flexibility

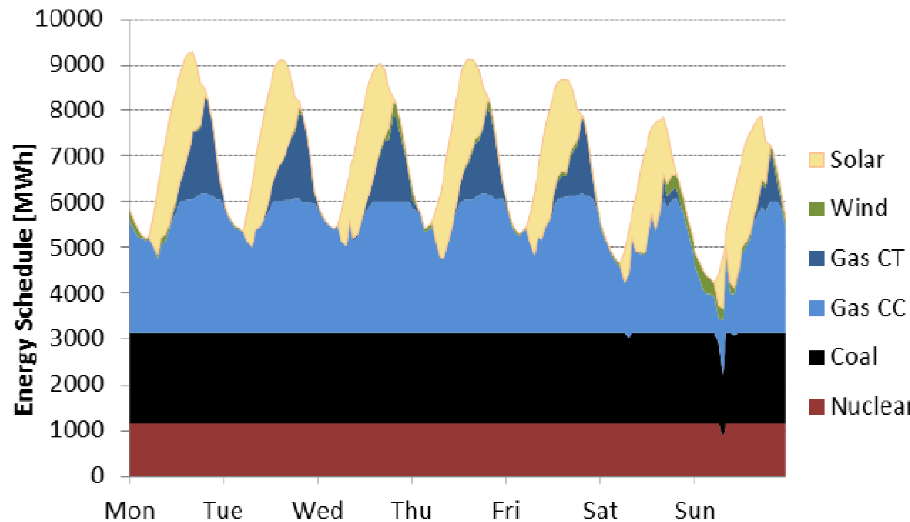
Low PV





High PV (flex nuclear)





Main Results with Base Assumptions

	No PV	Low PV	High PV (Const. Nucl.)	High PV (Flex. Nucl.)
Balancing reserves and CPS2				
Maximum balancing reserve up (MW)	187	278	556	556
Average balancing reserve up (MW)	132	171	241	241
CPS2 score (must be >90)	96.1	95.8	92.6	92.6
Integration cost				
Balancing reserve cost ($/MWh-PV)	N/A	1.61	3.56	1.11
DA forecast error cost ($/MWh-PV)	N/A	0.27	0.21	0.63
Total PV integration cost ($/MWh-PV)	N/A	1.88	3.77	1.74
Renewable curtailment				
Renewable curtailment (% ren. energy)	0%	2.9%	17.8%	3.4%

Increased balancing reserves and day-ahead forecast errors increase costs

Table 21. Total Costs and Solar PV Integration Costs for Low-PV and High-PV Scenarios

	Total Cost, *TC* ($M/yr)			Integration Cost ($/MWh-PV)		
Scenario	TC_p	TC_{HA}	TC_{DA}	BR Increase (HA) $(TC_{HA} - TC_p)/E_{pv}$	Forecast Error (DA) $(TC_{DA} - TC_{HA})/E_{pv}$	Total $(TC_{DA} - TC_p)/E_{pv}$
Low PV	888.4	894.1	895.1	1.61	0.27	1.88
High PV (Const. Nucl)	797.8	822.5	823.9	3.56	0.21	3.77
High PV (Flex. Nucl.)	777.9	785.6	790.0	1.11	0.63	1.74

Total costs *without accounting for forecast errors or sub-hourly variability*

Total costs *with additional balancing reserves to account for sub-hourly variability*

Total costs *with balancing reserves and day-ahead forecast errors*

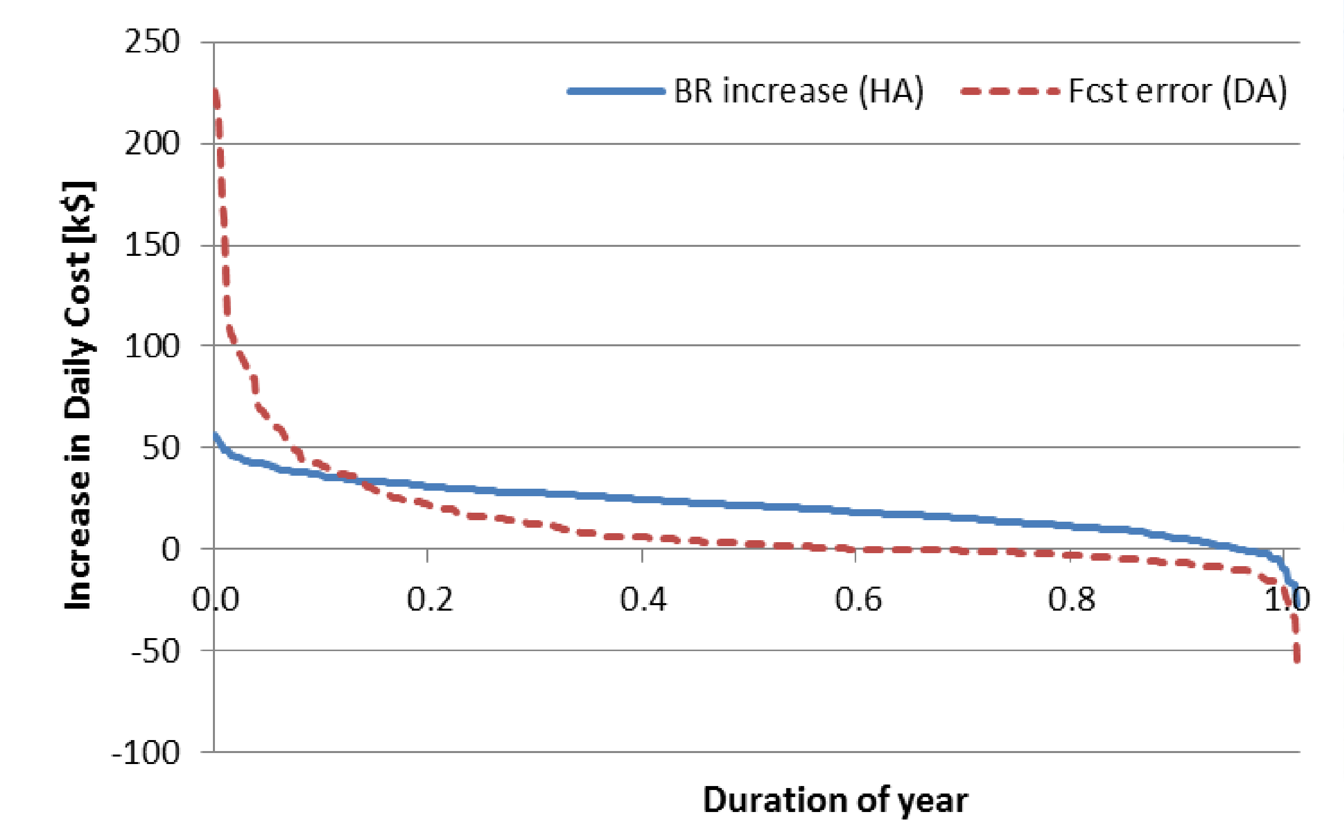
Incremental costs due to balancing reserves

Incremental costs due to day-ahead forecast errors

Incremental costs due to both additional balancing reserves and day-ahead forecast errors

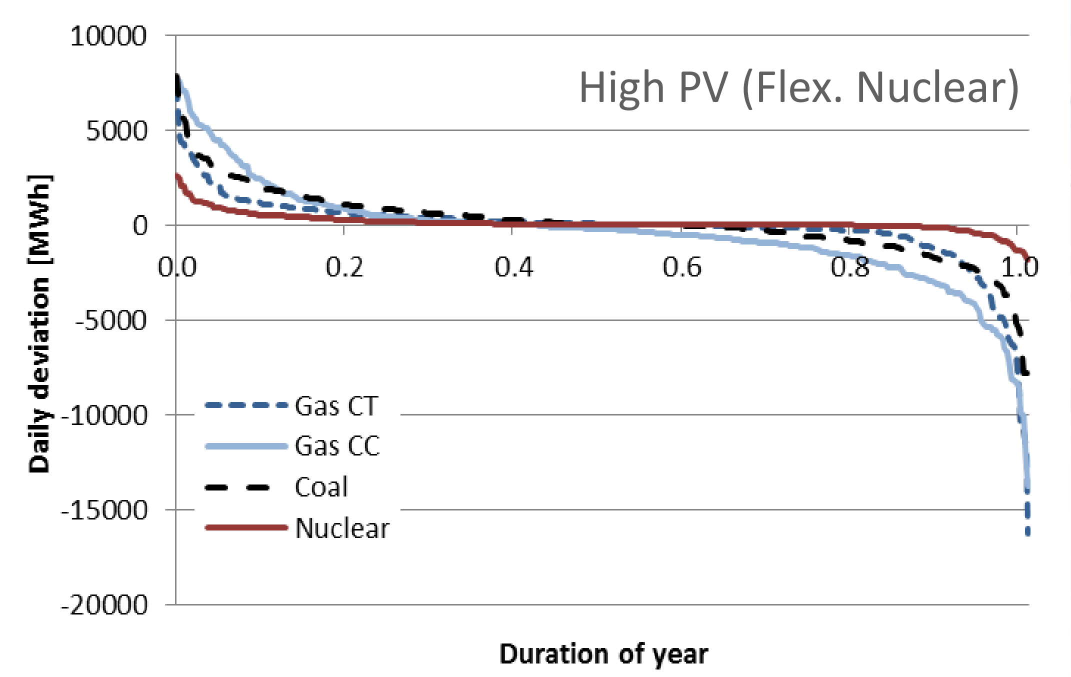
Large Variations in Daily Integration Costs

High PV (flex nuclear):



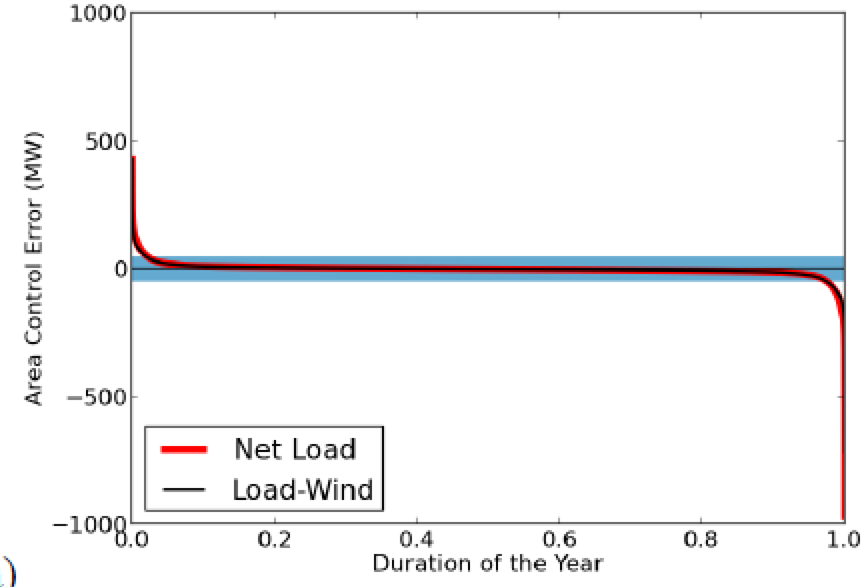
BR integration costs higher most days, but forecasting error integration costs more volatile with higher extremes

Day-ahead Forecast Errors Managed through Re-dispatch of Generation: Impact on Natural Gas Storage

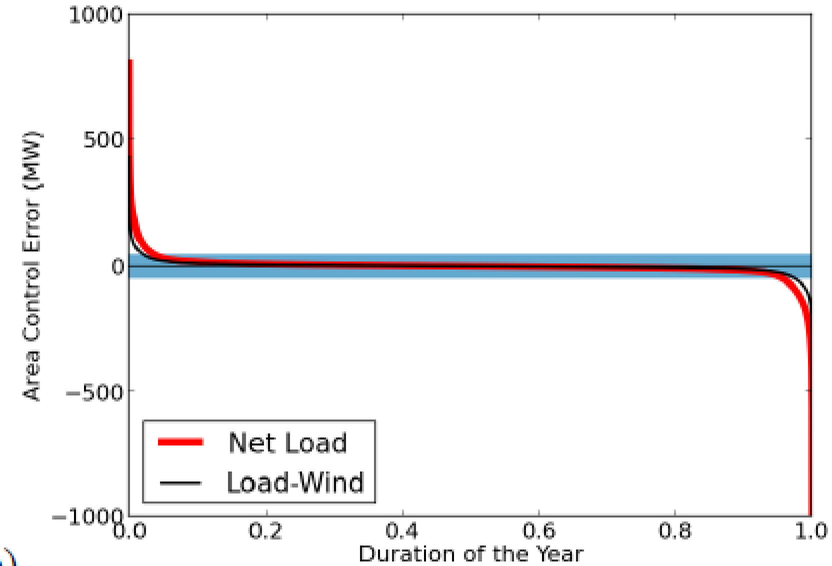


Natural Gas Consumption [Bcf/day]	Low-PV Scenario	High-PV (Flex. Nucl.) Scenario
Max. daily gas consumption	0.69	0.58
Avg. daily gas consumption	0.19	0.15
Max. daily storage withdrawal	0.10	0.12
Max. daily storage injection	0.27	0.28

NERC Reliability Compliance is Achieved, though Performance Degrades with High PV



(a)



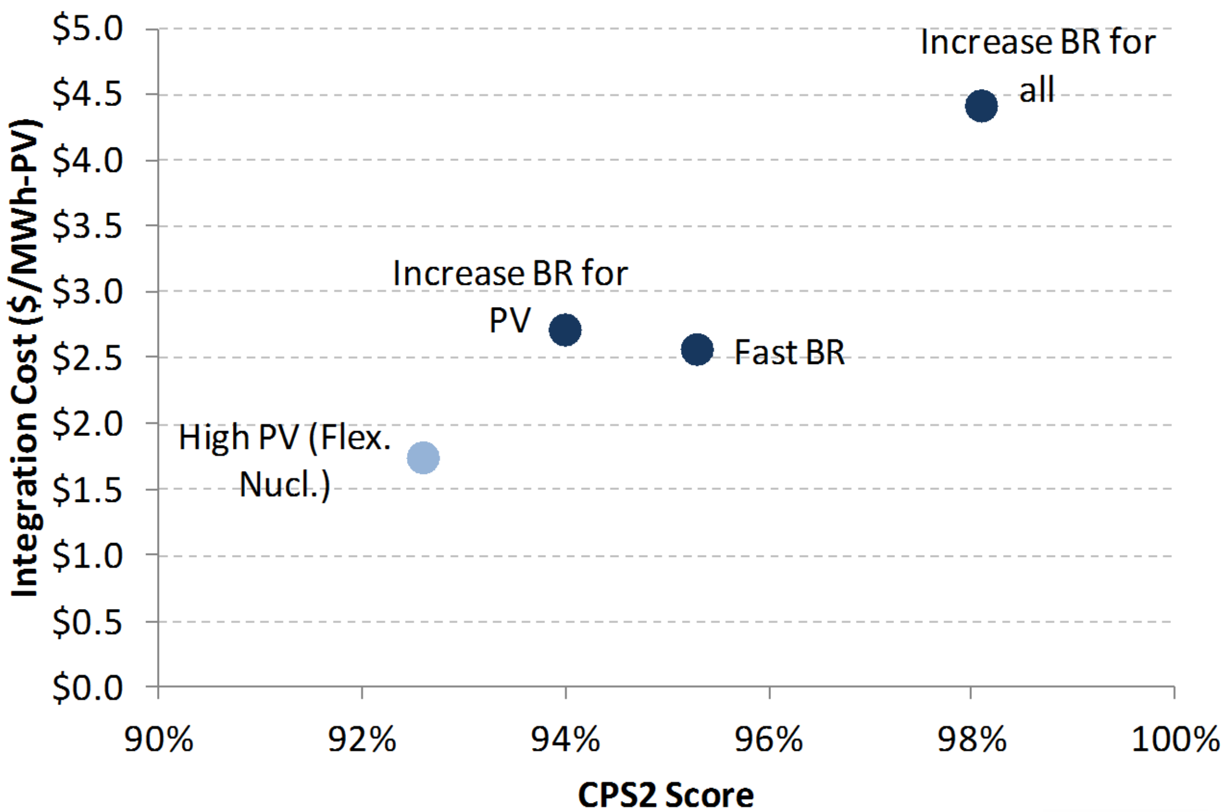
(b)

Note: Blue bar represents the L_{10} parameter for APS, which is assumed to be 46 MW

Figure 13. ACE Resulting from a Mismatch between Deviations from the HA Schedule and Deployment of Balancing Reserves in RT in the Low-PV Scenario (a) and the High-PV Scenario (b)

Scenario	CPS 2 (must be >90%)		Approximate CPS1 (must be >100	
	Load-Wind	Net Load	Load-Wind	Net Load
Low-PV	96.1%	95.8%	184	182
High-PV	96.1%	92.6%	184	169

Reliability Performance (CPS2) can be Improved, but it Comes with Increased Integration Costs



- **Increase BR for PV:** Increase balancing reserves to cover 98% of PV deviations from schedule
- **Fast BR:** Require balancing reserves to be fully deployed in 5-min (rather than 10-min)
- **Increase BR for all:** Increase balancing reserves to cover 99.8% of load, wind, and PV deviations

Sensitivity Analysis (high PV w/flex nuclear): Integration Costs

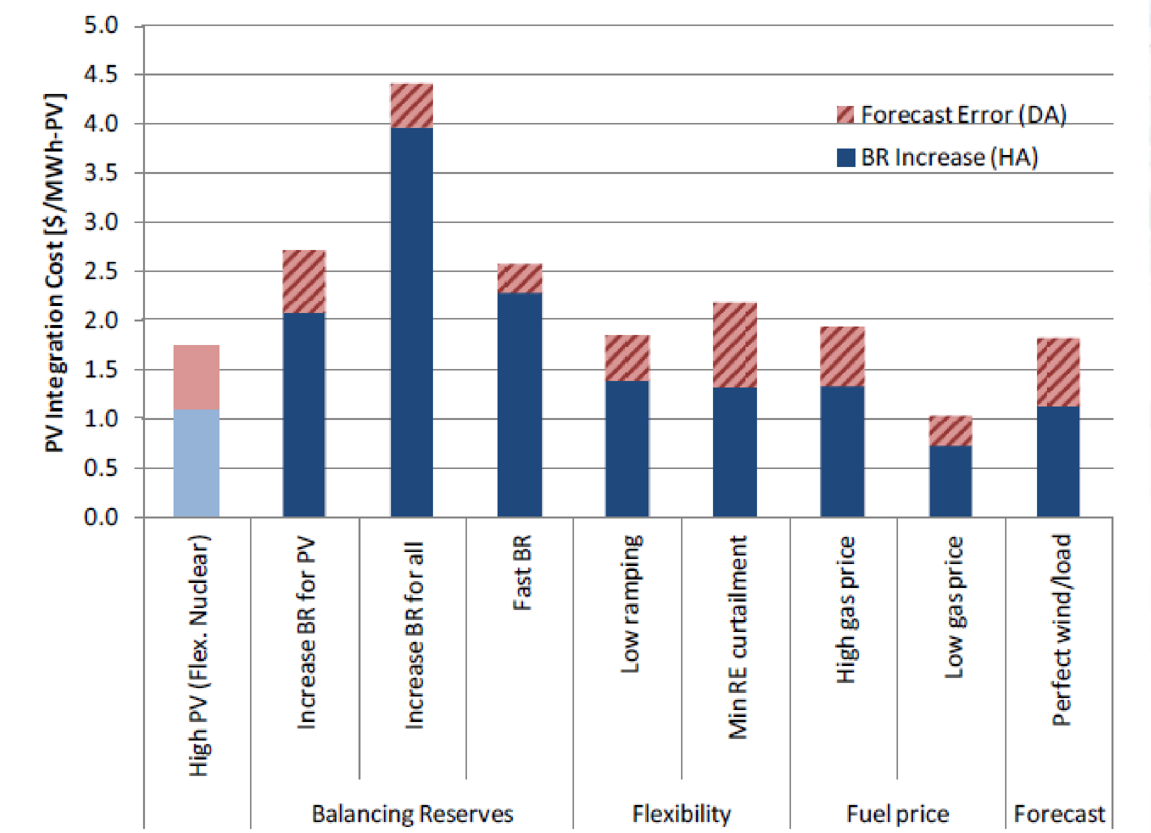


Figure 17. PV Integration Cost Estimates for High-PV (2027) Sensitivity Cases

- **Low ramping:**
  Use lower ramp rate estimate for thermal generation
- **Min RE curtailment:**
  Add significant penalty for curtailing renewable resources
- **High gas price:**
  Increase gas price by 25% (from $5.85 to 7.31/MMBtu)
- **Low gas price:**
  Decrease gas price to $4.00/MMBtu and increase coal price from $1.96 to $3.00 / MMBtu
- **Perfect wind/load:**
  Assume perfect load and wind forecasts in DA and HA

Sensitivity Analysis (high PV w/flex nuclear): Curtailment of Renewable Energy

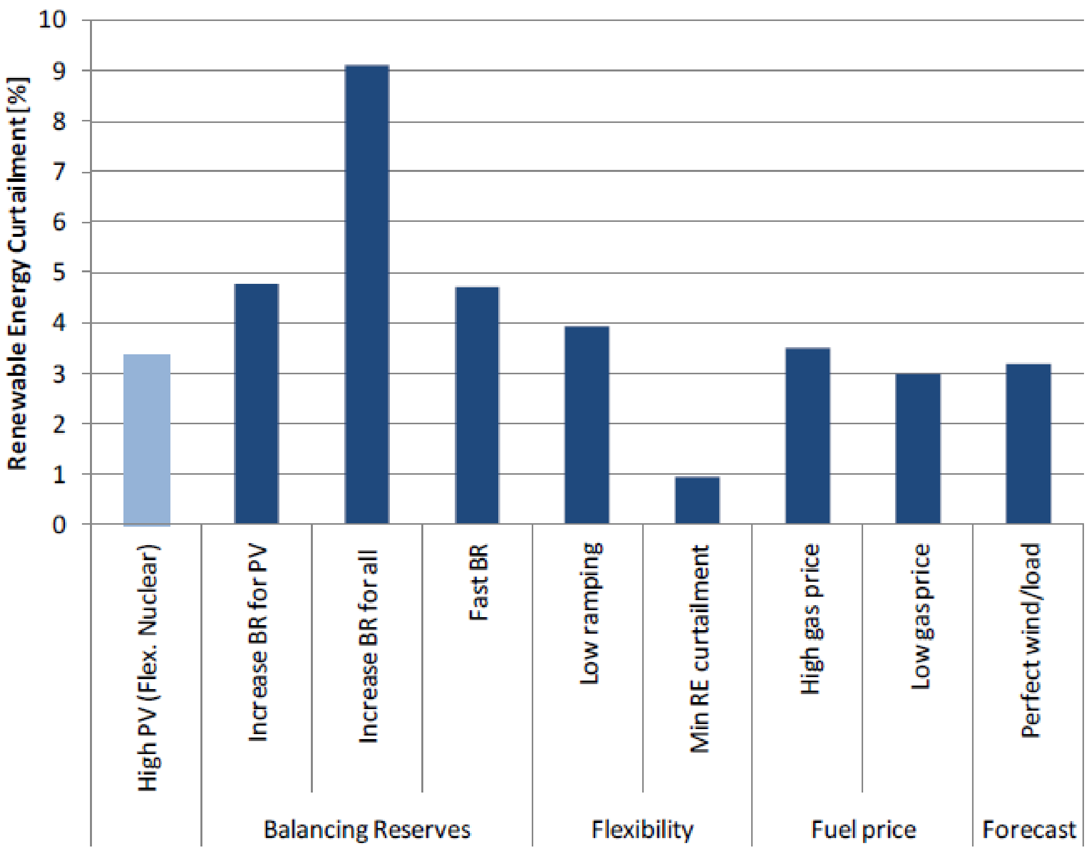


Figure 16. Renewable Energy Curtailment as a Percentage of Total Available Resources for High-PV (2027) Sensitivity Cases

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- **Perfect wind/load:**
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Recommendations and Areas for Future Work

- Flexibility in the downward direction may be a major challenge with high PV:
  - Identify potential buyers of surplus power (especially in spring season)
  - Evaluate downward balancing reserves from renewables, particularly during times when curtailment would otherwise be needed
  - Consider load shifting or energy storage
- Increased sub-hourly variability may be managed through alternatives to holding more balancing reserves:
  - Energy imbalance market can increase access to balancing resources
  - New NERC balancing standard may be less stringent than CPS2
- Consider alternative providers of reserves (demand response, renewables)
- Utilize probabilistic forecasts to reduce reserves on clear days
- Account for forecast errors in day-ahead commitment, consider stochastic unit commitment

Acknowledgements

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- The authors are solely responsible for the content of the analysis and any omissions or errors contained within it

Further details available in project report:

A. Mills, A. Botterud, J. Wu, Z. Zhou, B-M. Hodge, M. Heaney, "Integrating Solar PV in Utility System Operations, Report ANL/DIS-13/18, Argonne National Laboratory, Oct. 2013.

Online: http://www.osti.gov/scitech/biblio/1107495